

ADVANCED RANGE SAFETY SYSTEM FOR HIGH-ENERGY VEHICLES

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Abstract

The advanced range safety system project is a collaboration between the National Aeronautics and Space Administration and the United States Air Force to develop systems that would reduce costs and schedule for safety approval for new classes of unmanned high-energy vehicles. The mission-planning feature for this system would yield flight profiles that satisfy the mission requirements for the user while providing an increased quality of risk assessment, enhancing public safety. By improving the speed and accuracy of predicting risks to the public, mission planners would be able to expand flight envelopes significantly. Once in place, this system is expected to offer the flexibility of handling real-time risk management for the high-energy capabilities of hypersonic vehicles including autonomous return-from-orbit vehicles and extended flight profiles over land. Users of this system would include mission planners of Space Launch Initiative vehicles, space planes, and other high-energy vehicles. The real-time features of the system could make extended flight of a malfunctioning vehicle possible, in lieu of an immediate *terminate* decision. With this improved capability, the user would have more time for anomaly resolution and potential recovery of a malfunctioning vehicle.

Nomenclature

A_c	casualty or lethal area of the fragment
AFB	Air Force Base

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E_c	expectation of casualty
E_{cf}	expectation of casualty for one vehicle fragment
E_{cg}	expectation of casualty for one grid cell
$E_{c\beta}$	expectation of casualty for one debris class
P_d	population density
P_i	probability of impact
JARSS	Joint Advanced Range Safety System
JARSS-MP	JARSS Mission Planning element
JARSS-RT	JARSS Real Time element
NASA	National Aeronautics and Space Administration
RCC	Range Commander's Council
RSA	Range Safety Analyst
RSO	Range Safety Officer
U. S.	United States
$\Sigma_{\text{crossrange}}$	sum of crossrange possibilities
$\Sigma_{\text{downrange}}$	sum of downrange possibilities

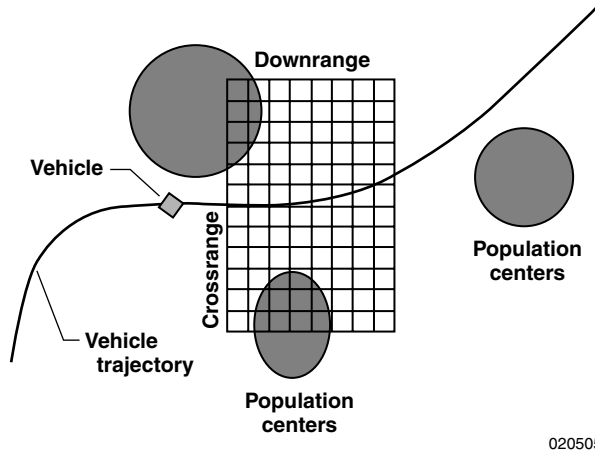
Key Words

JARSS, range safety, terminate, terminate lines, debris field, impact prediction, impact point, impact limit line, dynamic impact limit line, mission planning, risk assessment, real-time, maximum glide range, malfunction, mission boundary line, planned trajectory.

Introduction

Flight-testing of technologically advanced unmanned aircraft involves risk, both to the public and to high-value assets. While aiming for success, the risk to the public that could result from a test failure is a

legitimate possibility. Thus, range safety exists to maintain safe acceptance levels of risk to the public and to any high-value assets that are put in harms way because of a particular flight test. The Range Safety Analyst (RSA) is responsible for analyzing potential failures of technologically advanced aircraft to ensure that risk to the public and other high-value assets are maintained within the safety standards established by the U.S. Range Commander's Council (RCC). The expectation of casualty (E_c) is a measure of risks to the public used by the Range Safety organization. Figure 1 illustrates the methodology for calculating an E_c . It depicts a grid of cells centered about a nominal trajectory and then is overlaid on a map showing relative population densities.



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Figure 1. Notional calculation of expectation of casualty, E_c .

The E_c risk analysis process can be represented by simple equations. The E_c for one vehicle fragment (E_{cf}) is defined as the product of a probability of impact (P_i), the population density (P_d), and the fragment casualty area (A_c),

$$E_{cf} = (P_i) \cdot (P_d) \cdot (A_c) \quad (1)$$

The E_c for one debris class ($E_{c\beta}$) is obtained by accumulating the E_{cf} over all fragments in that class; and the expectation of casualty for one grid cell (E_{cg}) is obtained by accumulating $E_{c\beta}$ over all debris classes in that cell. Finally, E_{cg} is summed for all cells in a crossrange strip, and summed over all downrange strips to produce the total E_c ,

$$E_c = \sum_{\text{crossrange}} \sum_{\text{downrange}} E_{cg} \quad (2)$$

The advanced range safety system discussed in this paper is a tool that would be capable of estimating mission risks both in mission planning and in real time. The system consists of two elements, the mission planning element and real-time element. The mission planning element would enable mission planners to quickly and accurately develop a set of flight profiles that would meet both operational and range safety requirements. The real time element integrates real-time data input from tracking and telemetry data sources (ground or space-based) to generate a real-time debris field. Together the systems of this Joint Advanced Range Safety System (JARSS) project would enable the safe execution of unmanned high-energy projects, such as return from orbit, reusable launch vehicles, and space planes.

Requirements

The two primary functions of mission planning risk assessment and real-time risk management are required of this JARSS. To support these two primary functions, the JARSS must have a simulation interface capability that can aid in Range Safety Officer (RSO) training as well as support a frame-by-frame playback feature for post-mission assessment and accident investigation.

The JARSS simulation capability would allow the RSA the ability to study alternative mission trajectories and quickly assess the E_c values for comparison to identify the optimum path that would minimize risk to the public and property. This capability is an additional benefit, in that the quick trajectory simulation can be applied to both RSO training and near real-time mission risk assessment, which would allow mission modifications while the vehicle is in flight.

The JARSS Mission Planning (JARSS-MP) element would have the capability to analyze the risk to public and property and iteratively adjust the mission profile until both the range safety risk criteria and mission requirements are met. The JARSS-MP would require the combined use of several database elements in addition to optimization techniques that could converge on the most efficient and effective mission profile. The final optimum trajectory would then be used by the RSO in real-time to manage the risks of the mission. As a goal, the time to perform both the mission planning and mission risk estimation functions would be reduced by a factor of ten from present methods.

The displays to be developed during mission planning are to be validated for use by the RSO during training for any particular mission. The training feature of the

JARSS system is required to have the capability to directly receive input from a project for a high-fidelity simulation. This JARSS function would be useful to the RSO and other mission operations personnel in perfecting the flow of the mission long before the actual mission is flown.

As the mission is flown, JARSS-Real Time (RT) is required to present the RSO with a real-time debris field and population contours on a user-friendly display that would make flight considerably more manageable near population centers.

The JARSS-RT element requires a capability to record every input and output of the system at real-time data rates. This function would be helpful in analyzing system accuracy and comparing the mission planning data to the real-time data after a mission has been completed. Additionally, JARSS would have an innovative digital video-recording feature that would be capable of frame-by-frame playbacks to aid in accident investigation, lessons learned, and training.

Advanced Range Safety System Approach and Benefits

In order to develop a JARSS, several technological obstacles must be overcome. Such a system has yet to be developed and would represent a new state-of-the-art system for range safety throughout the United States National Range System. To implement the JARSS in the most effective manner, NASA has planned an approach to demonstrate proposed innovations that combine full-scale prototyping with evolutionary development. This phased approach is expected to be cost effective.

Phase one plans to develop the algorithms, models and functional prototypes for the JARSS. The algorithms and models developed will form the basis for the development of the real-time debris field as well as a real-time E_c . Algorithms and models to generate a real-time maximum-glide range cardioid will also be developed. No national range in the U.S. has tools or techniques to address the maximum-glide range capability of high-energy vehicles. For the sake of cost savings, many mathematical improvements and the testing necessary to certify this JARSS system as operational will be intentionally postponed. These algorithms include “wild-point editing,” “Kalman filtering,” and other enhancements necessary for a true real-time system.

Phase two is to develop the architecture for the real-time system. The primary user of phase two will be

the Range Safety Officer (RSO). The RSO is responsible for managing the risks to the public during flight operations. The goal of JARSS phase two is to demonstrate the technology for displaying a real-time debris field and a real-time E_c . The design for the real-time system would be tailored to the specific needs of high-energy vehicles. The design would include processing speeds that allow the data to be presented with minimal data latency and considerations of human factors in developing a functional RSO user interface.

Finally, the third phase is to develop a display for the RSO that would present the real-time information in a straightforward manner enabling the RSO to make the best-informed decisions with a minimum amount of screen clutter.

The benefits of this advanced range safety system would be to include a more effective approach for obtaining range safety approvals for flight plans, reduce cost and schedule, and provide improved situational awareness to the RSO during a mission. The JARSS would be capable of resolving public risks from multiple reentry scenarios in a matter of days as opposed to weeks. This capability would save both budget and schedule time for the project. The project mission planner and the range safety analyst would have the capability to analyze and adjust trajectories much more quickly. The resulting trajectory would comply with the strict public risk standards established by the U. S. RCC without compromising mission goals.

In real-time the JARSS could provide the RSO with a complete set of decision-making tools. These tools would enable the RSO to manage the real-time mission goals with a real-time assessment of risk to the public. This capability would give the RSO flexibility in assessing off-nominal vehicles. With the high quality of information available to the RSO from this system, it would become possible to extend flight to a malfunctioning vehicle, recovering additional telemetry data for anomaly reconstruction, and possibly even recovering the vehicle.

Design Approach

The basic JARSS design approach is an evolutionary development incorporating rapid prototyping. System requirements are first to be defined at a high level and then an integrated product team comprised of the developers and the intended system users (RSOs and RSAs) would be responsible for translating these requirements into the integrated low-level capabilities that meet operational needs cost-effectively.

JARSS would require a substantial amount of data describing the vehicle under test. This data traditionally includes: vehicle failure modes and failure probabilities, vehicle performance data for determining possible trajectories (both nominal and non-nominal) and enough structural data to estimate debris characteristics. Unlike traditional launch vehicles, the types of vehicles to be supported by JARSS may not have fully developed debris catalogs or historically-based failure probability models. Accordingly, JARSS would provide the analyst with tools to estimate potential fragment characteristics from high-level descriptive information such as weights and dimensions.

JARSS plans to make use of numerous databases (such as those listed below) developed and maintained by various government agencies. These databases would provide JARSS with worldwide terrain, climate, population, and other essential information.

- NOAA (National Oceanic and Atmospheric Administration) Terrain Base 94 Digital Terrain Model; for worldwide ground elevations
- NOAA (National Oceanic and Atmospheric Administration) Global Gridded Upper Air Statistics; for worldwide climatology
- NOAA (National Oceanic and Atmospheric Administration) Global Self-Consistent Hierarchical High-Resolution Shoreline; for land mass outlines
- ORNL (Oak Ridge National Laboratory) LandScan 2000 Global Population; for worldwide population
- NIMA (National Imagery and Mapping Agency) Vector map; for roads and other geographic features
- NIMA (National Imagery and Mapping Agency) Digital Aeronautical Flight Information File; for airspace features and airport locations

Mission planning is generally an iterative solution that starts with the nominal mission profile. The JARSS-MP plans to use a vehicle-characteristics database and the mission profile to develop a maximum-glide range and a maximum debris field dispersion for each instant along the trajectory. Used simultaneously, these attributes could define the total usable flight envelope. After the total flight envelope has been developed, the risk analysis can be fine-tuned using vehicle maximum stable malfunction turns to develop a statistical debris envelope along the flightpath of the vehicle at an analyst-specified confidence level.

The debris field would be comprised of a number of separate debris classes, with each class representing a number of physical fragments in a different ballistic characteristics group. The debris field accounts for state uncertainty (instrument error, data latency effects, etc.), breakup or explosion-induced velocities, drag, wind profile, ground blast, and debris bounce. This debris field would then be combined with a population database, along the mission profile, to yield the expectation of casualty, both in terms of expectations per mission hour and cumulatively for the total mission duration.

Figure 2 illustrates an example of an unmanned autonomous vehicle (UAV) showing the various elements that are considered during mission planning. The vehicle program office provides a planned trajectory to the range safety analyst. In some cases the autonomous or ad hoc maneuvers might be planned. In this case, the analyst would work with the vehicle program office to define a free flight maneuvering polygon that bounds such areas of operation. The primary objective of the range safety analyst is to determine if the planned trajectory can be flown with an acceptable level of risk and to establish rules and constraints to ensure public safety.

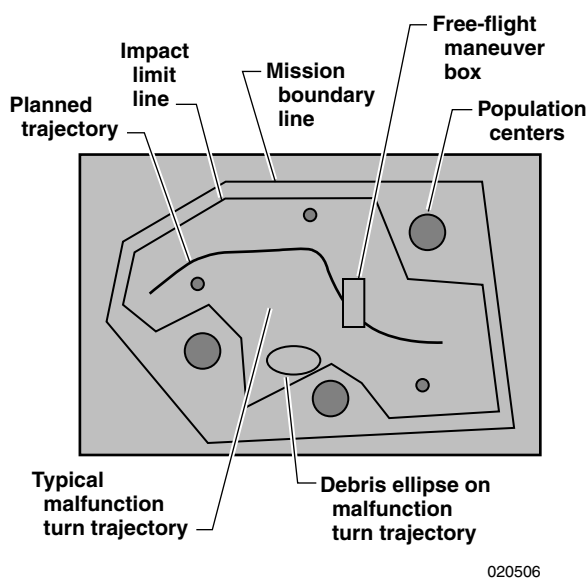


Figure 2. Notional JARSS mission planning display.

First the analyst defines a mission boundary line that conservatively encloses both the planned area of operation and any population center that might be placed at risk. Clearly extreme distant population centers need not be considered when evaluating debris hazards for unmanned high-energy vehicle operations at Edwards AFB. The analyst's task is then to establish an impact limit line that will ensure that an acceptable level of risk is achieved.

The JARSS Mission Planning element would establish the impact limit line by simulating vehicle malfunction turns at analyst-selected points along the planned trajectory. A debris field would be periodically generated as the vehicle proceeds along the malfunction trajectory. By numerical integration of the debris field a probability-of-impact contour is established over the affected geographical area. These contours would then be combined with population data to develop an expectation of casualty. An impact limit line point is identified when the expectation of casualty exceeds an analyst-specified threshold. Using this JARSS capability would yield a significant refinement in managing the risk to the public, which allows the establishment of a much less-conservative mission boundary.

The JARSS-RT element would improve range safety risk management. The inputs to the Real-Time element of JARSS would consist of setup and configuration data produced by the Mission Planning element, real-time sensor data, and RSO control inputs. The setup and configuration inputs would include selected topographic and population data; geographic and airspace features; the planned trajectory, mission boundary and impact limit lines; and other data. Real-time sensor inputs normally consist of a state vector consisting of position, velocity, and orientation information from various sources. RSO control inputs would include display selection, uncluttering operations, and tracking controls.

In general, a simulation need only be capable of supplying the real-time element of JARSS with compatible tracking data to enable JARSS to participate in the simulation. For example, if the simulator can output a global-positioning-system (GPS)-derived state vector in a compatible format, JARSS could use this data for display. The JARSS integrated product team is evaluating technologies, including current Department of Defense-sponsored test and simulation interoperability middleware to allow JARSS to ingest simulation and sensor data from other range facilities with minimum incremental engineering effort.

A simple low-cost, low-maintenance, off-the-shelf hardware architecture is envisioned for the JARSS system. The final, deployed JARSS hardware architecture would be determined during the evolutionary development process.

The notional JARSS-MP element would consist of analyst workstations and an internet connection, large computation and file servers, a printer and plotter, and a digital video disc-random access memory (DVD-ROM) for archive recording and for data transfer to the JARSS-RT element for training and mission execution.

Each string of the notional JARSS-RT element would consist of dual high-performance graphical displays and processors, a touch-screen controller, a digital video recording and playback unit, large computational and file servers, a printer and plotter, interfaces for weather and other data, and a JARSS-MP workstation to support short turn-around analysis requirements.

Range Safety Officer Display

The JARSS RSO display is being designed to give the RSO an optimal "big-picture" view of the mission. In addition, the RSO plans to have the capability to display detailed information about a specific event or time of flight during the mission. A conceptual real-time RSO display is shown in figure 3.

An impact prediction would be presented in real-time for the RSO to estimate the most likely location of impact for a fragment or group of fragments. An elliptical or other statistical region surrounding the impact locations could also be shown to account for uncertainties in initial state, aerodynamic characteristics, or atmospheric conditions as shown in figure 3 (conceptual real-time user display). A geographic distribution of the impact locations and their associated uncertainty regions for all of the fragments representing the vehicle (assuming a break-up in flight has occurred) is depicted as the vehicle debris field.

Two forms of debris fields would be available to the RSO in real-time: Real-Time and Catastrophic. The Real-Time Debris Field is a predictive tool used to make flight termination decisions. The real-time debris field would emphasize preventing exposure of ground populations to unacceptable risks. The catastrophic debris field is a predictive tool used to support post-incident search and recovery operations and to establish and maintain exclusion zones to protect against hazards associated with still-falling debris. The debris field would be used in conjunction with the

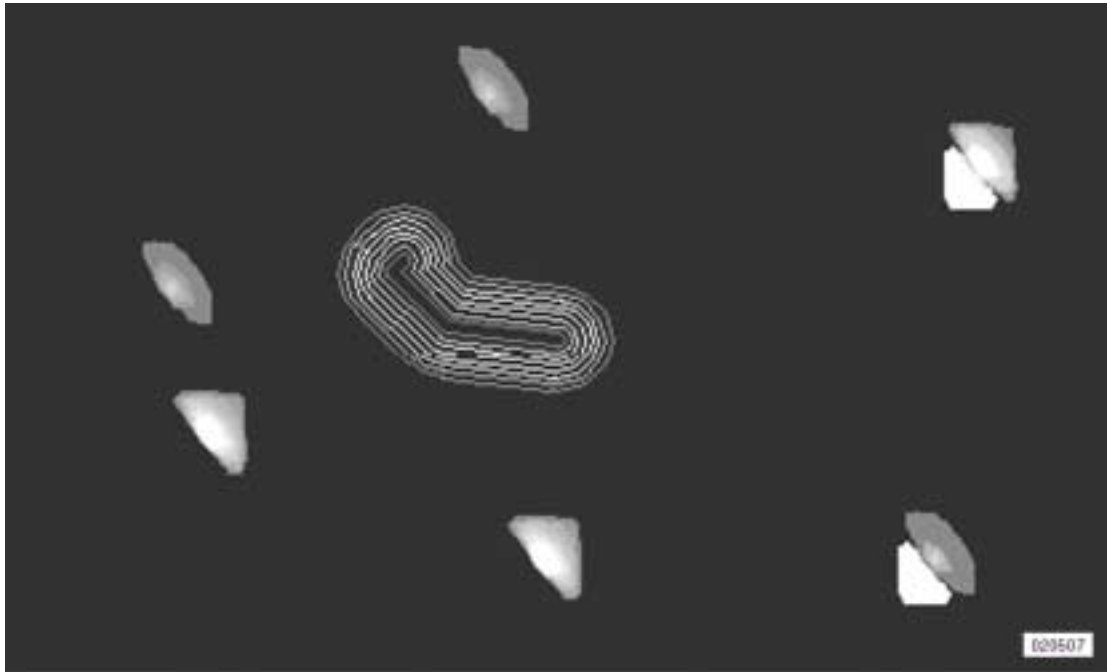


Figure 3. Notional JARSS real-time display.

population concentration display to determine the mission boundaries both in real-time and mission planning.

A population concentration display would show the RSO and RSA a graphical indication (intensity of shading or color) that indicates the concentration of population in a geographic area. The population concentration display would be derived from a grid of population counts. As the Real-Time Debris Field intersects population centers, the E_c for a particular time of flight would be generated. During mission planning, potential flight paths or trajectories that exceed E_c criteria would be excluded from consideration by forming a mission boundary line.

Mission boundary lines are to be developed by the RSA during the mission planning phase and presented to the RSO in real-time. Mission boundary lines establish the analytical limits for a given mission.

Populations and property outside of these lines would not be considered in the risk analysis. The mission boundary line is drawn based on maximum vehicle range along the planned flightpath of the vehicle. (If the vehicle cannot realistically hazard an area, then not putting the area into the detailed risk assessment yields some economies.)

The planned flightpath of the vehicle is determined by the nominal ground track and altitude profile the vehicle would fly to perform the mission. Using the planned flightpath two other useful user interfaces are planned to be developed: the Maximum Glide Range Cardioid and the vehicle Abort Ellipses.

The Maximum Glide Range Cardioid is depicted by a cardioid figure drawn on the surface of the Earth that indicates the maximum distance that a vehicle could glide unpowered assuming the most efficient possible translation of kinetic to potential energy and the most efficient possible glide thereafter. The Abort Ellipses are depicted by elliptical regions and indicate the most probable impact point for a vehicle, assuming that its parachute or other abort system activates and that the vehicle then descends intact.

Figures 4 and 5 are actual screen captures from the JARSS Real-Time RSO display prototype. They depict a simulated re-entry from polar orbit landing at Edwards, AFB.

In figure 4, the vehicle has just begun its re-entry. The present position of the vehicle is indicated by the cone. A white line indicates the predicted flightpath of the vehicle to its impact point. The impact point is indicated by the circle. Please note, that this rapid prototype

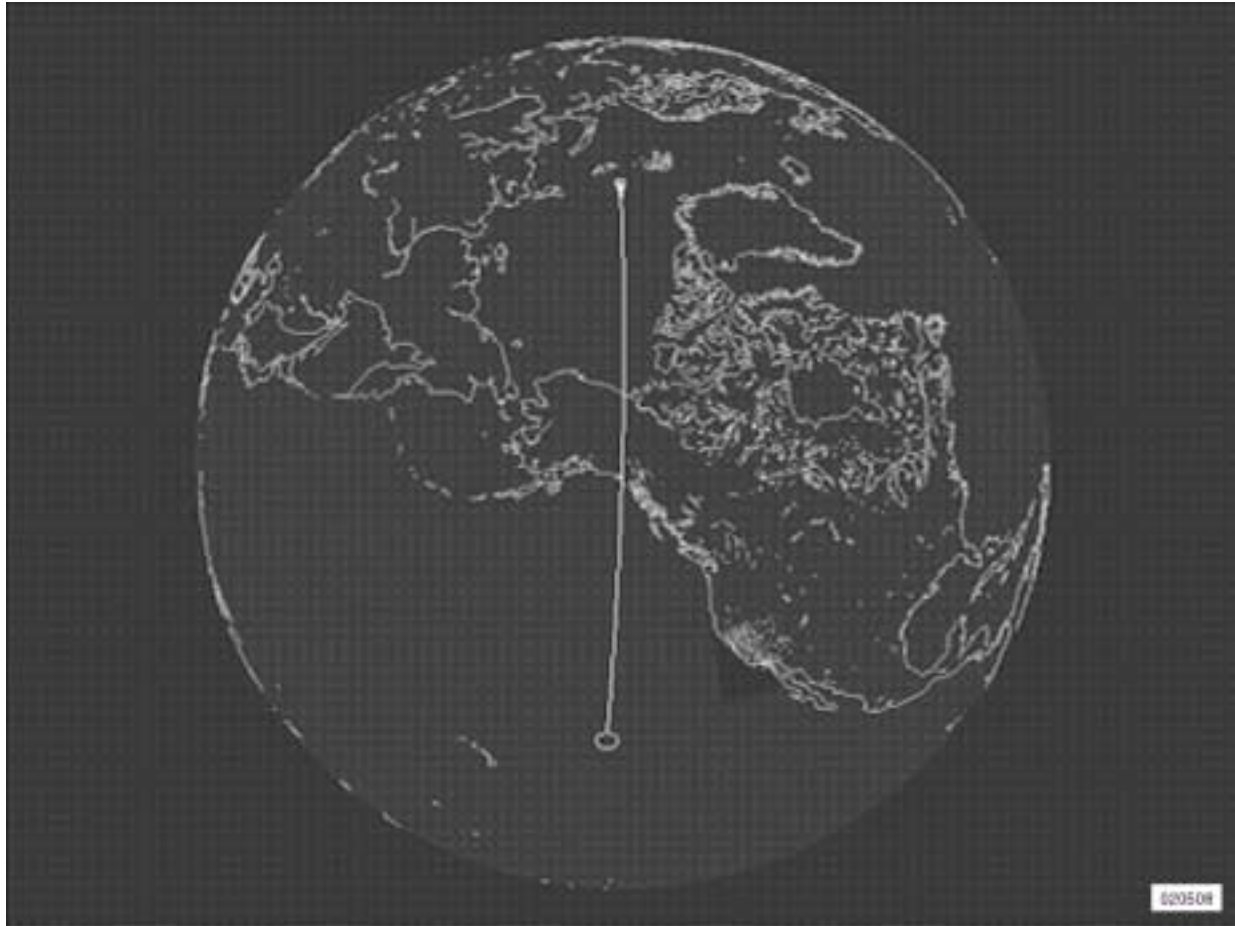


Figure 4. Vehicle on deorbit burn trajectory.

simply computed a Keplerian impact point rather than the aerodynamically adjusted impact point.

Observe that for most of the globe, we simply present shorelines. In the Edwards AFB area additional details are provided, as can be seen in the black patch covering southern California.

The next illustration is a close-up as the vehicle glides to landing at Edwards, AFB. The gridlines are topologic contours. The gray-scale coloring is a logarithmic encoding of population density with white indicating the heaviest concentrations of population.



Figure 5. Close-up as vehicle glides to landing at Edwards, AFB.

Project Status

Substantial proof-of-concept prototyping and analyses have already been completed for JARSS. A NASA-lead integrated project team has identified the key requirements for both the Mission Planning and Real-Time elements of JARSS. A task is presently underway to provide an interim mission planning tool to serve as a pathfinder for implementing issues in performance and accuracy trade-offs.

Basic prototypes of the RSO displays have been completed and a notional hardware architecture has been defined for JARSS-RT. Key algorithmic components of JARSS-MP, such as fragment impact prediction and impact probability integration, have been prototyped.

Conclusion

The JARSS program plans to develop a state-of-the-art range safety mission planning, analysis,

and risk management system. This new capability would allow the development of advanced high-energy vehicle envelope expansion, as well as expand the capabilities for space lift initiative development, test, and operations. JARSS would streamline and significantly reduce the time-line as well as the cost of the range safety analysis for mission planning, return-from-orbit scenarios, and analysis of malfunctioning vehicle contingencies, while maintaining a high degree of confidence in risk assessment and real-time risk management for public safety.

Reference

¹Brencher, A., J. Collins, and K. Koldzy, *Hazard Analysis of Commercial Space Transportation*, May 1988. Technical Report PB93-199040; DOT-SRP-88-08-VOL-1-2-3.

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